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Comment on the Updated CDF “Ghost” Events

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Abstract

In 2008 the CDF Collaboration announced the discovery of an excess of events with two or more muons, dubbed “ghost” events for their unusual properties. In a recent update, CDF finds that the azimuthal angle distribution between the primary (trigger) muons is significantly more back-to-back than that of all known sources of di-muon backgrounds. Here we show that this angular distribution cannot be reproduced in models where the muons are produced in the decays of relatively light X -particles: all models of this kind also predict a much broader distribution than that found by CDF. We conclude that the CDF measurement cannot be described via the annihilation of strongly interacting partons, and thus seems to be in conflict with basic tenets of QCD.

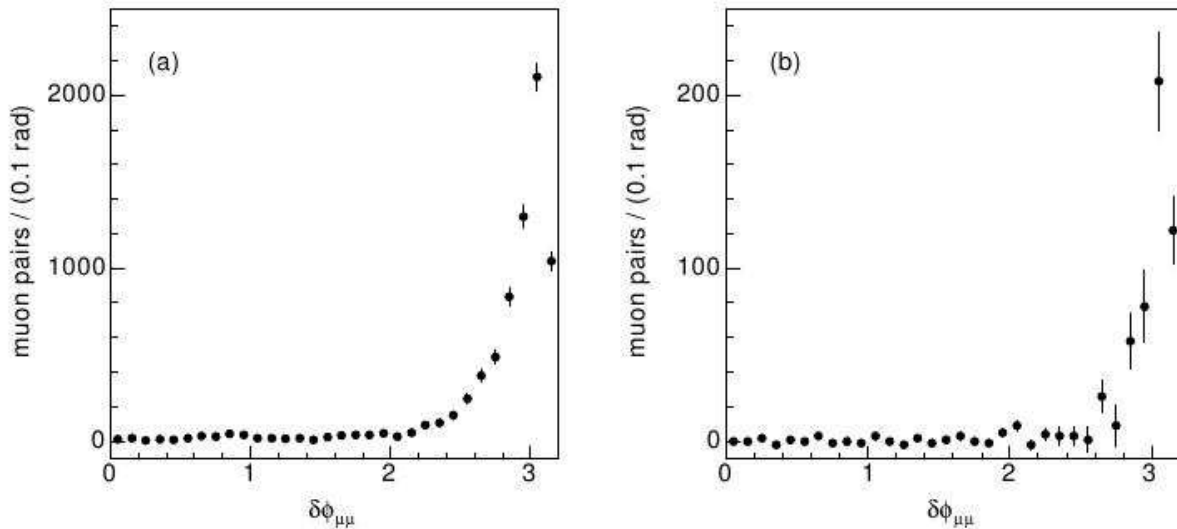


Figure 1: The measured distribution of the azimuthal angle $\delta\phi_{\mu\mu}$ between the two primary muons. Each primary muon should be accompanied by at least one (**left**) or two (**right**) additional muons. [Fig. 4 from [2].]

In 2008 the CDF Collaboration announced the discovery of a very large sample of events with two or more muons that could not be explained by known production mechanisms (chiefly heavy flavor and Drell–Yan production) [1]. The two muons with the highest transverse momenta in an event, the primary muons, have to pass the following cuts: Each primary muon should have a transverse momentum $p_T \geq 3 \text{ GeV}$ and a pseudorapidity $|\eta| \leq 0.7$. Additionally their combined invariant mass should be in the range $5 \text{ GeV} < m_{\mu\mu} \leq 80 \text{ GeV}$. These unexplained events were called “ghost” events due to their unusual properties. Among other things, at least one of the two primary (trigger) muons is produced outside the (inner part of the) microvertex detector; also, there are roughly equal numbers of like-sign and opposite-sign primary di-muon pairs. Altogether, CDF estimated that 84895 ± 4829 events with two or more muons belong to this “ghost” category, for an integrated luminosity of 742 pb^{-1} . An unexpectedly large fraction of these events contains additional muons (with $p_T \geq 2 \text{ GeV}$, $|\eta| \leq 1.1$) in 36.8° cones around the primary muons.

After reviewing their estimate of the QCD production and investigating a bigger data sample CDF reduced the estimate for the total number of ghost events to 54437 ± 14171 for an integrated luminosity of 1426 pb^{-1} [2]. Note that this is less than four standard deviations away from zero. However, 12169 ± 1319 of these events have at least one additional muon. Looking at the azimuthal angle $\delta\phi_{\mu\mu}$ between the two primary muons they noticed that the distribution differs from known QCD production for the subset of ghost events where *each* primary muon is accompanied by at least one additional muon, see Fig. 1: most primary muons are very nearly back to back, whereas conventional sources of multi-muon events have much broader distributions in $\delta\phi_{\mu\mu}$. CDF concludes from this that at least this subsample of “ghost” events cannot be explained from known sources, e.g. through mis-identification or late decays of hadrons.

In 2010 we constructed some models that could explain most of the (publicly available)

features of the original ghost events [3]. We used these models to predict the number of “ghost” events predicted in several older experiments. The fact that at least one of the muons originated more than 15 mm away from the primary vertex, and the large fraction of like-sign events, should make these events readily recognizable.

In order to simulate “ghost” events in Herwig++ [4] we introduced a rather long-lived bosonic X particle, whose pair production and subsequent decay (with $c\tau_X \gtrsim 15$ mm) should be responsible for the primary muon pair. X should be a Majorana particle to account for the equal number of same-sign and opposite-sign primary muon pairs. We assumed that each X particle decays into four elementary fermions in order to allow a high number of muons in the final state. We considered several different production mechanisms and decay possibilities for the X particles. Within a given scenario the mass and branching ratios of the X particle were determined by the measured invariant mass distribution of all muons contained in 36.8° cones around the primary muons and by the measured muon multiplicity distribution.

Here we compute the $\delta\phi_{\mu\mu}$ distribution of the primary muons for events where each primary muon is accompanied by at least one additional muon predicted by these models, and compare with the measurements shown in Fig. 1. We first consider a simple model which reproduces more than 90 % of the original ghost events with the process $q\bar{q} \rightarrow XX$, assuming a differential S -wave cross section:

$$\frac{d\sigma(q\bar{q} \rightarrow XX)}{d\cos\theta} = N_{q\bar{q}} \cdot \frac{\beta}{\hat{s}} = N_{q\bar{q}} \cdot \frac{\sqrt{1 - \frac{4m_X^2}{\hat{s}}}}{\hat{s}}.$$

Here \hat{s} is the squared partonic center of mass energy, β is the velocity of the X particles in the partonic center of mass frame, and $N_{q\bar{q}}$ a constant fitted to the cross section for “ghost” events given in ref. [1]; the shape of the $\delta\phi_{\mu\mu}$ distribution does not depend on the value of this constant. The X mass is $m_X = 1.8 \text{ GeV}/c^2$; see ref. [3] for further details. Our model allows X decays into one, two or four muons. Since we want to study events where each primary muon is accompanied by (at least) one additional muon, we here force both X bosons to decay in two muons with equal probability either via $X \rightarrow \mu^- \mu^+ u \bar{u}$ or $X \rightarrow \mu^- \mu^+ d \bar{d}$. We simulated 5 million events, most of which do not pass the cuts described above.

The predicted $\delta\phi_{\mu\mu}$ distribution after cuts is shown in Fig. 2. Evidently the distribution is much broader than that shown in the left frame of Fig. 1: this model predicts the cross section to remain sizable out to $\delta\phi \approx 2$ rad, whereas the CDF distribution essentially cuts off at $\delta\phi \approx 2.6$ rad.

The broadening of the $\delta\phi_{\mu\mu}$ distribution is due to three physical effects. First, even in the simplest parton level calculation, only the two X -particles are produced back-to-back in the transverse plane. The decay of the X particles into two (or more) muons (plus additional particles) generically adds a component to the p_T vector of the muons which is orthogonal to that of the parent X -particle. Second, perturbative gluon radiation, in particular initial state radiation, gives a transverse “kick” to the X pair. However, this is not sufficient to describe, e.g., Drell-Yan production adequately in the region of small p_T of the lepton pair. To this end, event generator programs allow the colliding partons to have an “intrinsic” p_T of typically one or two GeV, which gives an additional transverse kick to the X pair; we modeled this using the default settings of Herwig++. The second and third effect therefore lead to a transverse opening angle between the two X particles that is less than π ; for given p_T of the X pair this effect will be smaller for larger p_T of each X particle.

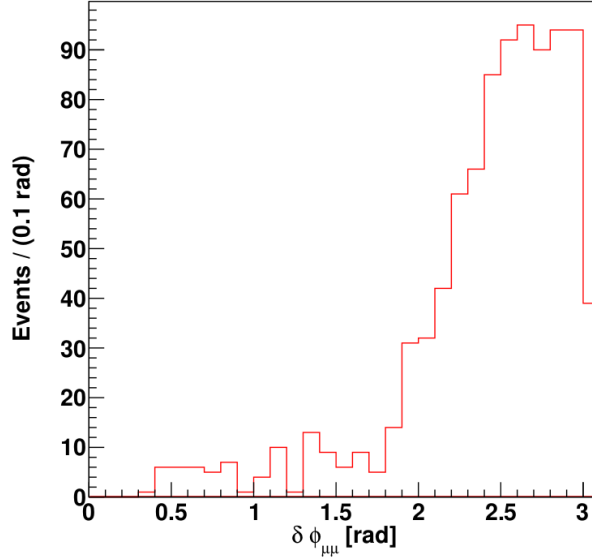


Figure 2: The distribution of the azimuthal angle $\delta\phi_{\mu\mu}$ between the two primary muons for the simple model. 36.8° cones around the primary muons should contain at least one additional muon each.

This simple model does not describe the original ghost events with higher muon multiplicities very well. This includes the invariant mass distribution of all muons in events where each primary muon is accompanied by at least one additional muon: the distribution predicted by this simple model peaks at smaller values, and drops off faster towards large values, than the distributions published in the original “ghost” analysis do [3]. In order to produce more events with large invariant mass, we therefore also consider a more sophisticated model, where X pair production proceeds via a broad resonance Y . The corresponding cross section is [3]

$$\frac{d\sigma(q\bar{q} \rightarrow Y \rightarrow XX)}{d\cos\theta} = N_{q\bar{q}}^{BW} \cdot \frac{\hat{s}^2}{(\hat{s} - m_Y^2)^2 + \Gamma_Y^2 m_Y^2} \cdot \frac{\sqrt{1 - \frac{4m_X^2}{\hat{s}}}}{\hat{s}},$$

where the constant $N_{q\bar{q}}^{BW}$ is again chosen to match the original ghost cross section. Y is a resonance with the mass $m_Y = 110$ GeV and width $\Gamma_Y = 110$ GeV, and $m_X = 4.6$ GeV. In ref. [3] we also modified the X decay branching ratios relative to the simple model, allowing decays where muon number is violated; this allowed us to reproduce the large fraction of “ghost” events where a primary muon is accompanied by a nearby secondary muon with the same charge. However, for the purpose of the present analysis the charges of the muons are irrelevant, so we focus on the decay mode $X \rightarrow \tau^+\tau^-\mu^+\mu^-$. The simulation of 5 million events leads to the $\delta\phi_{\mu\mu}$ distribution after cuts shown in Fig. 3.

Evidently this model does not describe the measured distribution shown in Fig. 1, either; the distribution is again much broader than the measurement, although slightly narrower than that predicted by the simple model. Note that in spite of the larger value of m_X the Q -value of the decay is actually somewhat smaller than in the simple model, reducing the difference between $\delta\phi_{XX}$ and $\delta\phi_{\mu\mu}$. Moreover, due to the Breit–Wigner form of the cross section, X -particles are

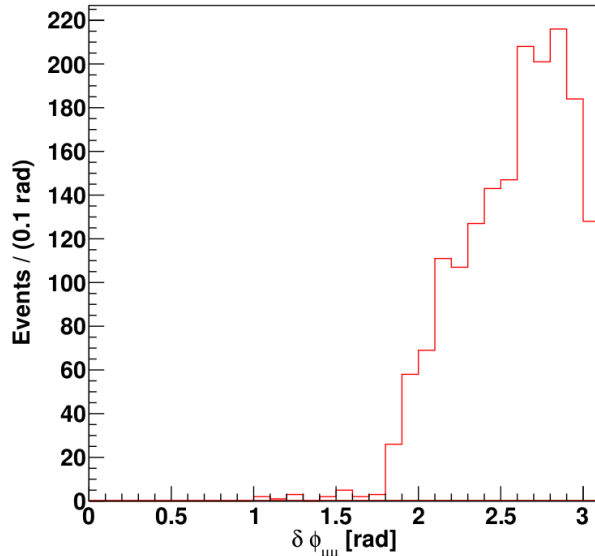


Figure 3: As in Fig. 2, but for the more sophisticated model.

now often produced with significant transverse momentum. This is required to reproduce the multi-muon invariant mass distribution shown in ref. [1]; it also reduces the effect of a fixed transverse “kick”, e.g. due to initial state radiation, on $\delta\phi_{\mu\mu}$.

It seems very difficult to generate a significantly narrower $\delta\phi_{\mu\mu}$ distribution, as required to reproduce the distributions shown in [2], without distorting the multi-muon invariant mass distributions within the cones around the primary muons or within the entire event, and/or without violating basic tenets of QCD. In particular, further increasing the average p_T of the X -particles would increase the invariant mass of all muons in the event too much; conversely, further decreasing the Q -value of X -decays would make the invariant mass distribution of muons inside the cones around the primary muons too soft.¹ Finally, choosing a $q\bar{q}$ initial state already minimizes QCD initial state radiation; gluons radiate considerably more, leading to an even broader distribution.

We therefore conclude that it is very difficult, if not impossible, to reproduce the $\delta\phi_{\mu\mu}$ distribution of the CDF “ghost” events within a quantum field theoretical model.

Acknowledgments

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¹Here we are assuming that the improved background estimate of ref. [2] does not greatly distort the shapes of these invariant mass distributions presented in the original analysis [1]. Unfortunately the update [2] only presents distributions in $\delta\phi_{\mu\mu}$; no invariant mass distributions are given.

References

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